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FLOW-RESISTANCE CHARACTERISTICS OF "W" OXYGEN MASKS

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ABSTRACT

The flow-resistance characteristics of the newly-designed "W" oxygen mask have been compared to those of the standard P/Q mask. With the mask or its components fixed in appropriate sealing plates, the cavity pressures required to achieve static flows were measured. For the dynamic test, a carbon-dioxide rebreathe system was used. Both types of mask satisfied Air Standardization Coordinating Committee criteria for allowable flow resistance. Although the mask cavity pressures were similar for inspiratory flows, the "W" mask required substantially less pressure than the P/Q mask for expiratory flow. Analysis of events within breaths suggested that inertial resistance contributes to the mask cavity pressures developed.

INTRODUCTION

To prevent hypoxemia during routine flight, it is recommended that aviators breathe supplemental oxygen at a concentration which maintains the alveolar oxygen tension equivalent to that obtained with air at 1,525 m. (1). Of the various oxygen delivery systems that can meet this physiological requirement, the diluter-demand type is preferred over continuous flow methods because it conserves gas by delivering oxygen only as needed. For such systems to be acceptable, however, they must not only be capable of meeting physiological demands, but must do so without imposing excessive resistance to breathing. Since the total pressure differential across a system at any flow is the sum of pressure differentials across its parts, reducing the impedance anywhere in the system will be advantageous.

Recently David Carter Associates (DCA) of the United Kingdom developed a new oxygen mask which is being considered for use by the Royal Air Force (RAF) and the Canadian Forces (CF). The advantages of the new "W" mask (Figure 1a) over the traditional P/Q (Figure 1b) and current CF (Figure 1c) masks are:

(a) all valves are mounted on a single block to facilitate maintenance and repair;

(b) replacement of natural rubber with silicone rubber for the face seal to improve its durability;

(c) use of a lighter expiratory valve.

It is the purpose of this report to describe the flow-resistance characteristics of the W mask. The following tests were performed:

(a) static assessment of W mask:

  (i) inspiratory and expiratory valves;
  (ii) expiratory valve with compensation pressure;
  (iii) assembled mask with and without regulator hose;

(b) static assessment of assembled P/Q mask;

(c) dynamic tests on the assembled W mask.

METHODS

Static Tests

The performance of each valve and of the whole mask assembly was assessed in the static mode. In this arrangement, air flow through the system was held constant for several seconds while mask

cavity pressure and flow were recorded. The flows ranged in steps from 10 to 300 l/min. Both an ascending and descending pattern for flow was used in each test.

Valve resistance. Measurement of the resistances to flow of the inspiratory, expiratory, and anti-suffocation valves was made by securing the valve holding block (centre, Figure 2) in the sealing device especially made for this purpose by DCA (Figures 3a and 3b). Valve pressure was taken via the corresponding side ports.

Mask resistance. The resistance of the whole mask assembly was determined using a double-plate sealing device (Figure 4a). The inner plate was fitted inside the face seal of the mask while the outer plate was fastened on top to produce a leak-free system (Figure 4b). Pressure in the mask cavity was measured through a short metal cannula penetrating the two plates. A standard mask hose (45.7 cm long) with its connector and retaining cord was attached to a piezometer ring which in turn was fitted to the intake port of the mask. The hose was allowed to hang freely.

Inspiratory tests. Inspiratory air flow was produced with a domestic vacuum cleaner (Portapower, Hoover, Burlington, Ont.) and controlled at the desired level using a rotameter (Flowrator, Fischer-Porter, Hatboro, PA), a three-way stopcock (#2100 Hans-Rudolf, Vacumed, Ventura, CA), and rubber tubing (1.9 cm inside diameter, Warren E. Collins, Braintree, MA). Air pressure was measured using a variable reluctance transducer (MP-45) and carrier demodulator (CD-19) system (Validyne Engineering, Northridge, CA). Output signals were recorded on a polygraph (Model R612, Beckman Instruments, Schiller Park, IL).

Expiracory tests. For the expiratory tests, gas from a cylinder of compressed air entered the mask cavity through the tube fitting of the sealing plate. When compensation pressure was required, the apparatus shown in Figure 5 was used. Air from a second compressed gas source was directed to a parallel system. One branch consisted of a piece of copper pipe (140 cm long, 10 mm id) immersed in water which was contained in a larger plastic pipe (130 cm long, 75 mm id). The other branch was fitted to one arm of a U-tube water manometer (95 cm long). A third air line made of tygon tubing (3 mm id) was connected to the compensation port to apply pressure on the back of the spring-loaded expiratory valve. The magnitude of the compensation pressure was set by adjusting the length of copper pipe immersed in water and monitoring pressure at the manometer. This test could be performed on both the isolated valve in its holding block or on the valve in the mask assembly.

Dynamic Tests

For the dynamic test, a wide range of ventilatory flows was required. A carbon dioxide rebreathing technique was used to produce hyperpnea as arranged in Figure 6. Since the expiratory valve has no

accessible port, collection of exhaled gas was achieved by placing the oronasal mask in a clear vinyl (12 gauge) envelope (Figure 7) with three outlets. The mask hose was clamped to the mask's inspiratory port through the first outlet and the sealing plates were positioned through the second one. A polyvinylchloride coupler was fitted through the third outlet to direct the expired gas. The inspiratory and expiratory hoses were connected to a plastic T-piece, itself secured to an 8-litre bag made of light, polyurethane-coated nylon (NATO stock # 8305-21-876-1620). The air flow output of the sealing plate was attached to a Fleisch #3 pneumotachograph (Bionetics, Montreal, Que.) and to a larger rubber mouthpiece. All sources of flow resistance excluding those inherent to the mask and its hose were kept to a minimum. Tidal volume, through changes in bag volume, was measured by air displacement from the closed glass bottle with a dry rolling-seal spirometer (P.K. Morgan, Gillingham, England). Because the oxygen in the bag was not being replenished, the subject's arterial hemoglobin saturation was monitored with an ear oximeter (Model 47201A, Hewlett-Packard, Waltham, MA) for safety. Air pressure was measured with the equipment described earlier.

Before the test, the bag was fully inflated with air. The subject was informed of what sensations to expect during the rebreathing period so that he would respond normally to the increasing concentration of inspired carbon dioxide. Breathing on the system commenced from the subject's residual lung volume position. He was instructed to continue for as long as possible without incurring undue discomfort. Mask cavity pressure, respiratory air flow, inspired volume (ATPD), and oxyhemoglobin saturation were recorded continuously. All instrumentation was calibrated before and after each test.

RESULTS

Static Tests

The results obtained from two W oxygen masks, one P/Q oxygen mask, and those from one DCA inspiratory valve are contained in Figure 8. The inspiratory valve requires a mask cavity pressure of approximately 0.3 cm H_2O to open. From this level, inspiratory pressure increases curvilinearly with changes in flow. Since flow resistance is calculated as P/ V, the slopes of the pressure-flow relationships are convenient units for comparison. The resistances in ranges of low and high flow rates are summarized in Table 1. There is less resistance with flow change at low rates than at high rates. The test condition also influences the pressure required at a given level of flow. Inspiratory resistance is progressively increased over that of the valve alone in the case of the whole mask assembly and then with the addition of the mask hose. Since the results of the P/Q mask are virtually superimposed over those of the W mask, there is no difference in the inspiratory resistance.

The expiratory measurements for the DCA valve and the two types of oxygen mask are shown in Figure 9. The opening pressure ofthis valve is approximately 1.2 cm H_2O. For the DCA valve and the W mask, there is little relative change in expiratory pressure for flows up to 150 l/min. With flows above this level, there are greater changes in pressure. The pressure measured in the mask cavities increased at a more rapid rate than that for the valve. The changes in P/Q mask pressure are greater for given increments in flow in comparison to the W mask. The resistance values for these expiratory tests are summarized in Table 2.

The results for the anti-suffocation tests are depicted in Figure 10. As was found in the inspiratory and expiratory tests, the pressure increases with changes in flow occur at a lower rate for flows less than 150 l/min and at a higher rate for flows above 150 l/min. When the anti-suffocation valve is tested in the mask, the opening pressure is greater than when it is in the sealing device by 3-5 cm H_2O and 10-15 cm H_2O at low and high flows, respectively. Differences of these magnitudes were also found between the two masks. This is greater than might have been expected as based on the similarity demonstrated between masks A and B in the other bench tests. The resistance values for the anti-suffocation valves are shown in Table 3.

Figure 11 illustrates the effect of applying a compensation pressure to the back of the expiratory valve on W mask cavity pressure at different air flow rates. Typical changes are represented by the connecting line which starts at an air flow rate of 150 l/min at the bottom of the diagram. Mask cavity pressure is 2.5 cm H_2O initially. When a compensation pressure of 5 cm H_2O is added, flow is reduced to 145 l/min while mask cavity pressure increases to 7.5 cm H_2O. Flow through the mask is then manually restored to 150 l/min without noticeable change in mask cavity pressure. Flow is decreased to 112 l/min when 38 cm H_2O compensation pressure is applied, and mask cavity pressure is elevated to 41.5 cm H_2O. Similarly, after flow is restored to 150 l/min and compensation pressures of 64 and 94 cm H_2O are applied, flow is decreased to 110 and 88 l/min, respectively. Mean differences between the compensation pressures and mask cavity pressures were 3.4, 4.4, and 4.1 cm H_2O when the applied compensation pressures were 38, 64, and 94 cm H_2O, respectively.

Dynamic Tests

The results of the dynamic tests with the W mask B are depicted in Figures 12-15. Three representative breaths, reproduced from different stages of the dynamic test on one subject, are shown in Figure 12. During the second and third breaths illustrated, respiration was stimulated with carbon dioxide. To compare the dynamic responses with those of the static tests, mask cavity pressure was measured at that segment of the air flow cycle in which

velocity was constant. These pressures have been graphed in Figures 13 and 14 for inspiration and expiration, respectively. There is good agreement between the data of the static and the dynamic tests as indicated by the overlap of the data.

When air flow is not constant, mask cavity pressure can differ markedly from the steady flow-pressure relationship. Several breaths from each subject were analyzed at moments other than when flow was constant. This was performed for four segments over the inspiratory and expiratory phases. It appears that when the rate of change of air flow is less than 10 $1/sec^2$, mask cavity pressure remains similar to the steady flow measurements. When the rate of change approaches 20-30 $1/sec^2$, mask cavity pressure deviates from the original relationship. A sample analysis is contained in Figure 15. For this graph, mask cavity pressure and flow were measured every 0.04 sec throughout the inspiratory phase of two breaths occurring near the end of the dynamic test in one subject. Mask cavity pressure is greater than the constant flow-pressure relationship during gas volume acceleration, and less during deceleration. The maximum deviation occurred at the beginning of inspiration. Here, although the flow rate is low (approximately 20 l/min), the acceleration is high (32 and 27 $1/sec^2$). Maximum deceleration (12 and 10 $1/sec^2$) occurred toward the end of inspiration. Near the middle of inspiration, air flow is constant and mask cavity pressure then approaches the static test curve.

DISCUSSION

The aim of aircraft oxygen systems is to maintain the alveolar partial pressure of oxygen at a level which prevents hypoxemia. This should be achieved with minimal discomfort to aviators, including as little disruption as possible in their individual breathing patterns during flight. This investigation has examined one part of an oxygen system, the pressure-flow characteristics of the newly-designed W mask.

In order to achieve the above aims, the Air Standardization Coordinating Committee Working Party 61 (2) has recommended that the pressure in the mask-hose assembly should not exceed those listed in Table 4. Both the P/Q and W masks easily meet these criteria for inspiratory and expiratory flows. Whereas the resistance of the two masks is very similar over the range of inspiratory flows tested, the W version requires substantially less pressure for expiratory flow than the P/Q mask.

From the results of tests conducted at Royal Air Force Institute of Aviation Medicine, Farnborough, England (unpublished observations provided by Lazowski and Porlier), it is suggested that the performance of the W mask is partly related to its design and

partly to the expiratory valve. In Figure 16, a Normalair-Garrett (NGL) valve in the W mask reduces the expiratory resistance compared to the P/Q mask with its NGL valve. Pressure is further improved with replacement by a DCA expiratory valve. Our findings confirm these observations (Figure 17) that there is little difference in pressure between the masks during inspiration.

The results reported here are in general agreement with those measured by Normalair-Garrett Ltd (6). All pressure levels fall within the range that they observed for the static inspiratory and expiratory tests, and for the dynamic tests. A comparison is included in Table 5. In one anti-suffocation valve test, the flow recorded at -7 in. H_2O (-17 cm H_2O) of cavity pressure was 35 l/min, a value only half of that found by NGL. The other anti-suffocation valve performed as expected with a flow of 90 l/min. A second discrepancy was noted in the compensation pressure tests. It was observed that the expiratory mask cavity pressure exceeded the three compensation pressures by 1.6 in. H_2O (4.1 cm H_2O), unlike the NGL measurement of 0.2 in. H_2O (0.5 cm H_2O) (range -1.0 to 1.65 in. H_2O or -2.5 to 4.2 cm H_2O). There is no obvious reason for this difference. As a result of stricter schedule requirements agreed upon by DCA, RAF/IAM, NGL and Ministry of Defence/Aircrew Equipment, Research and Development, -2, U.K. (15 March 1983) compared to the ASCC standards, the NGL report concluded that the W mask is inadequate.

The possible consequences of increased resistance to breathing have been reviewed by Sharp and Ernsting (7). If the resistance is excessive, a pilot may increase respiratory muscle work in order to maintain alveolar ventilation. Alternatively, he may breathe more slowly to enhance comfort but with greater risk of hypoventilation which, in turn, can produce hypercapnia and hypoxemia. Although there are subjective sensations of resistance with present protective equipment, severe physiological disturbances appear to be avoided. To evaluate the level of resistance imposed by masks and hoses, the curvilinear relationships between mask cavity pressure and air flow stress the importance of knowing the range of flows typically experienced during flight. Harding (5) reported that peak flows were concentrated between 50 and 175 l/min. During aerial combat manoeuvres, flow may reach 400 l/min (4). As such, inspiratory mask cavity pressure could vary from -1 to -6 cm H_2O but pressures of -20 to -25 cm H_2O are also possible.

Before gas can be moved in a mechanical system such as the oronasal mask and hose assembly, pressure must be produced to overcome the opposing forces related to the instantaneous valve position, the instantaneous gas flow rate, and the instantaneous gas acceleration. Considering the inspiratory valve, it must first be opened before air can flow. From the graphs, the pressure required to maintain this minimally-open position in the W mask is approximately 0.3 cm H_2O. Next, for more air to flow through the valve, a greater

pressure must be provided. At 150 l/min, this pressure combined with the valve opening pressure totals approximately 4.3 cm H_2O. The increasing change in pressure for a given increment in flow is suggestive of non-laminar flow characteristics. Finally, when air is accelerated, inertia is developed by the mass of the air and the valve's diaphragm. The extra pressure required will be equal to the product of the mass and the acceleration level.

Due to the composite nature of the system as it was tested, each of the parts contributes additively to the overall resistance. In Figure 8, to achieve an inspiratory flow rate of 150 l/min through the mask requires 1.2 cm H_2O suction pressure over that needed for air flow through the valve only. The addition of the mask hose further increases resistance so that the total pressure necessary is 4.3 cm H_2O. This analysis applies similarly to the expiratory components and illustrates that overall reductions in the breathing resistance of protective equipment can be achieved with attention to their parts.

One aspect of breathing equipment performance which appears to have received little attention to date, although it has been recognized as being important (3), is the pressure required for gas acceleration. According to the classical definition, any mass in uniform motion will require extra force in order to alter its motion or position. In the respiratory system, this occurs when air flow is increased or decreased. When an oxygen mask is worn, cavity pressure during air flow is compounded by the inertia of the diaphragm in the valve. Figure 12 demonstrates this effect during the ventilatory cycle. Firstly, note that air flow rate is relatively stable during the middle of inspiration and expiration. Mask cavity pressure is also unchanged during this period and the relationship between pressure and flow replicates that found during the static bench tests. This means that neither the static nor the dynamic test is superior for assessing mask flow resistance when air flow rate is steady. Secondly, whenever flow rate is changing, by definition there is gas acceleration and deceleration. By constructing tangents on the flow record, the most rapid changes are found at the start of inspiration and expiration. It is at these moments that the pressure required to overcome inertial forces must be combined with the pressure necessary to overcome flow resistance. As can be seen in Figure 15, mask cavity pressure then exceeds the static relationship. At an inspiratory flow of 60 l/min, the mask cavity pressure required is approximately double that needed when there is no gas acceleration. This would be equivalent to inspiring at a constant rate of 100 l/min.

In conclusion, the cavity pressures were found to be comparable between the newly-designed W oxygen mask and the P/Q mask over a wide range of inspiratory flows. The W mask, however, requires less pressure than the P/Q mask for expiratory flows. The latter appears

related to both W mask design and a lighter DCA expiratory valve. Static and dynamic tests produced similar results for the flow-resistance characteristics but the latter tests highlight the greater mask cavity pressures generated during gas acceleration.

ACKNOWLEDGEMENTS

The authors thank Mcpl J. Lefebrve of the Medical Life Support Division for constructing the nylon rebreathing bag and mask envelope, and Mr. R. Cardin for his technical assistance.

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ANNEX

Figure 1a. Front view of W oxygen mask.

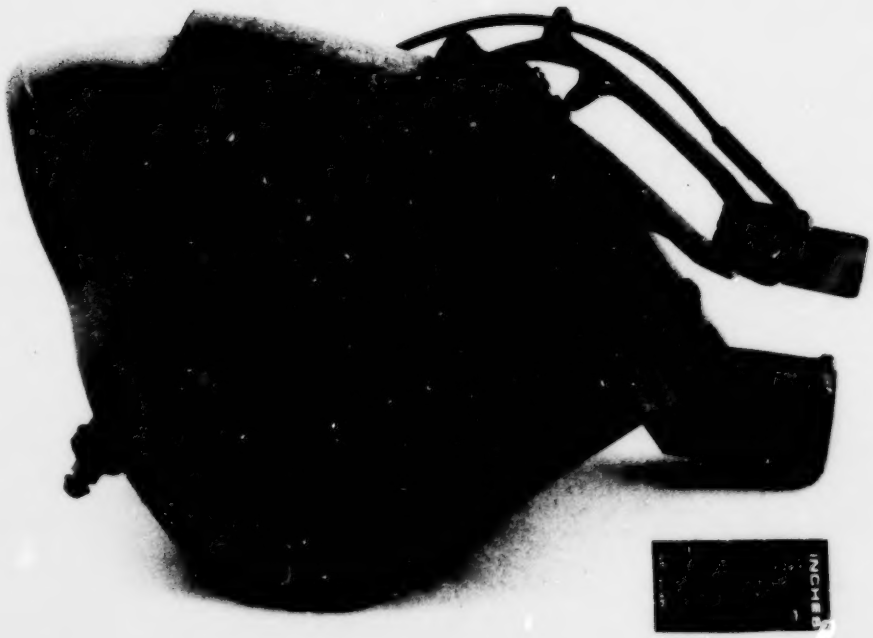

Figure 1a. Side view of W oxygen mask.

Figure 1a. Back view of W oxygen mask.

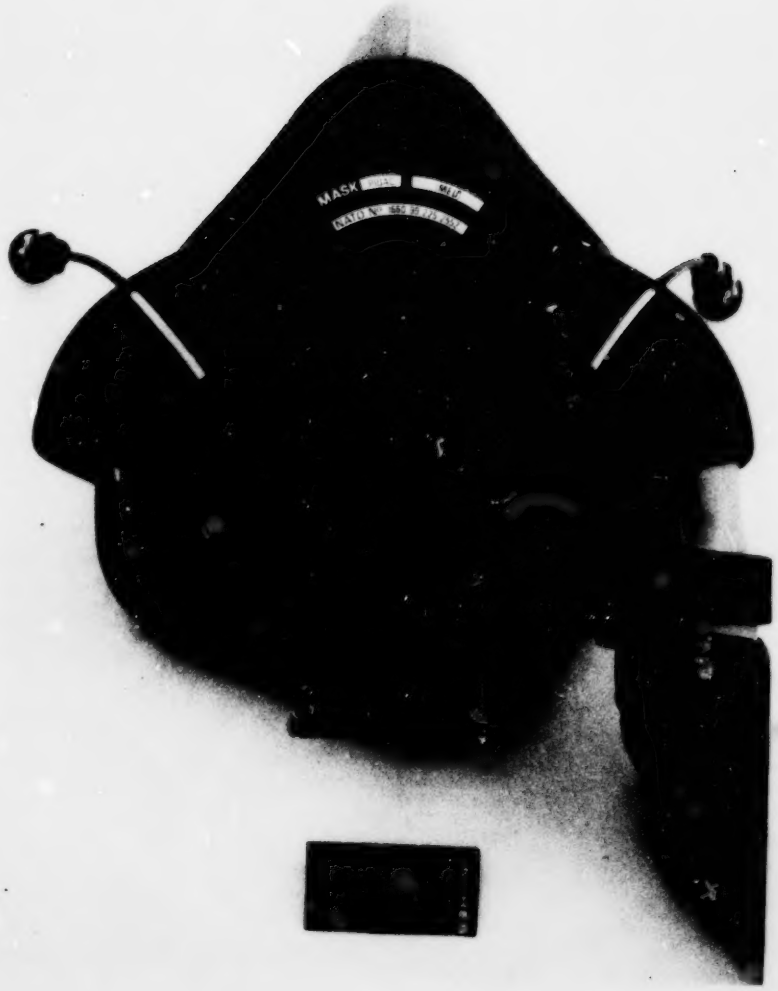

Figure 1b. Front view of P/Q oxygen mask.

Figure 1b. Side view of P/Q oxygen mask.

Figure 1b. Back view of P/Q oxygen mask.

Figure 1c. Front view of A13A oxygen mask.

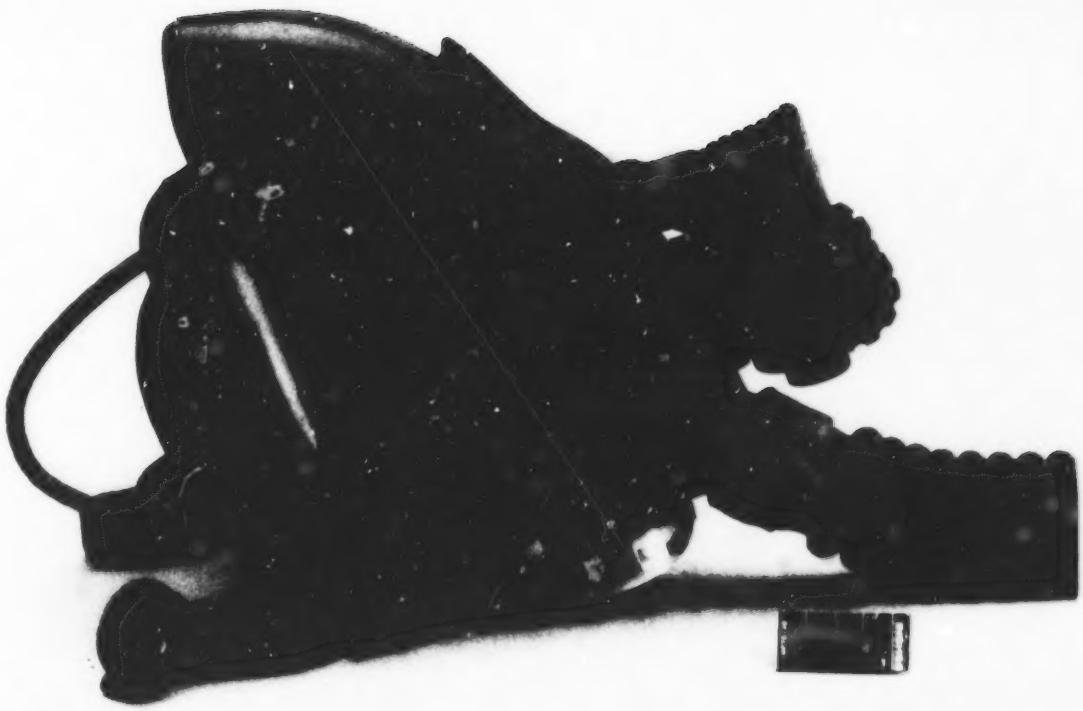

Figure 1c. Side view of A13A oxygen mask.

Figure 1c. Back view of A13A oxygen mask.

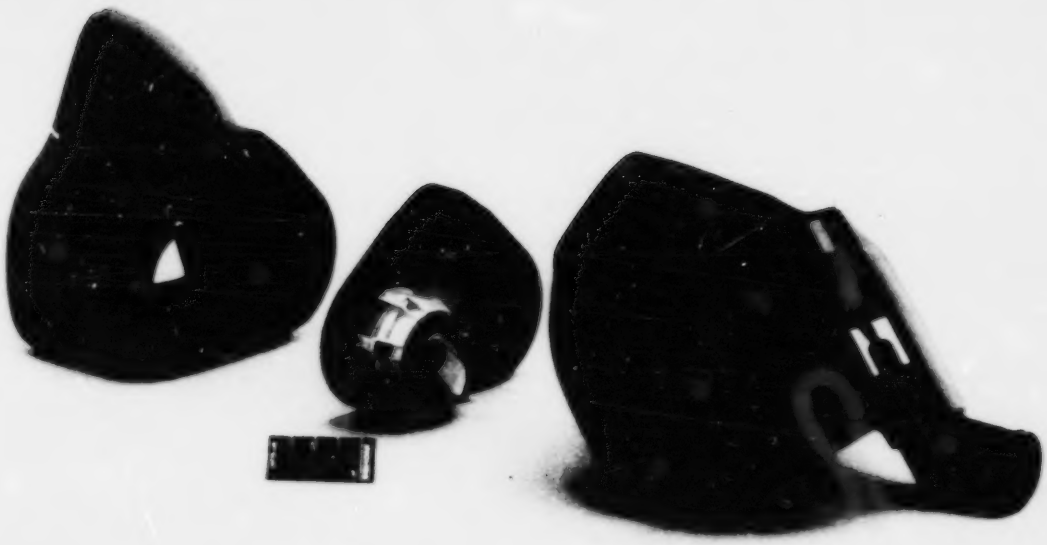

Figure 2. Components of W oxygen mask. From left to right, face piece, valve holding block, exoskeleton.

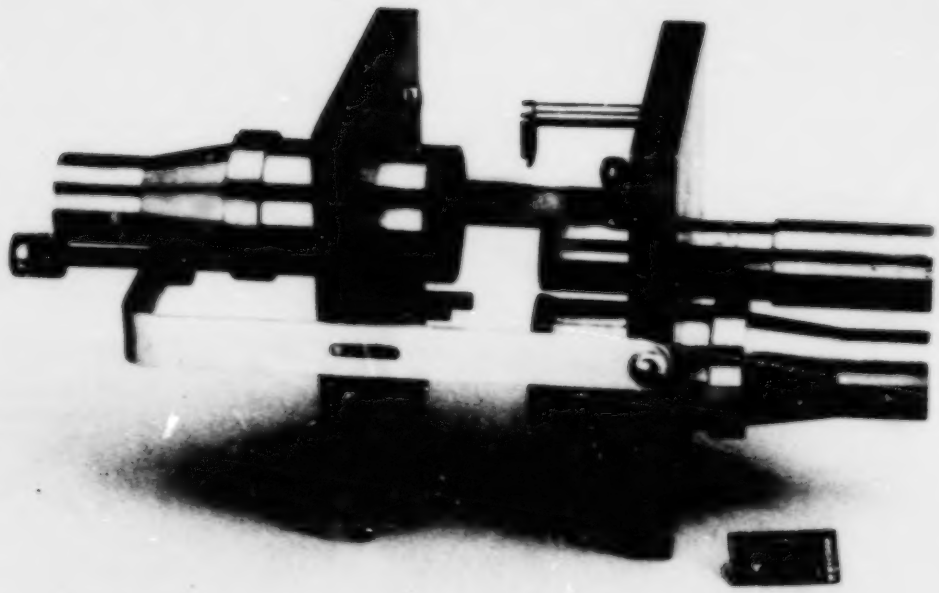

Figure 3a. Sealing device for DCA valve holding block.

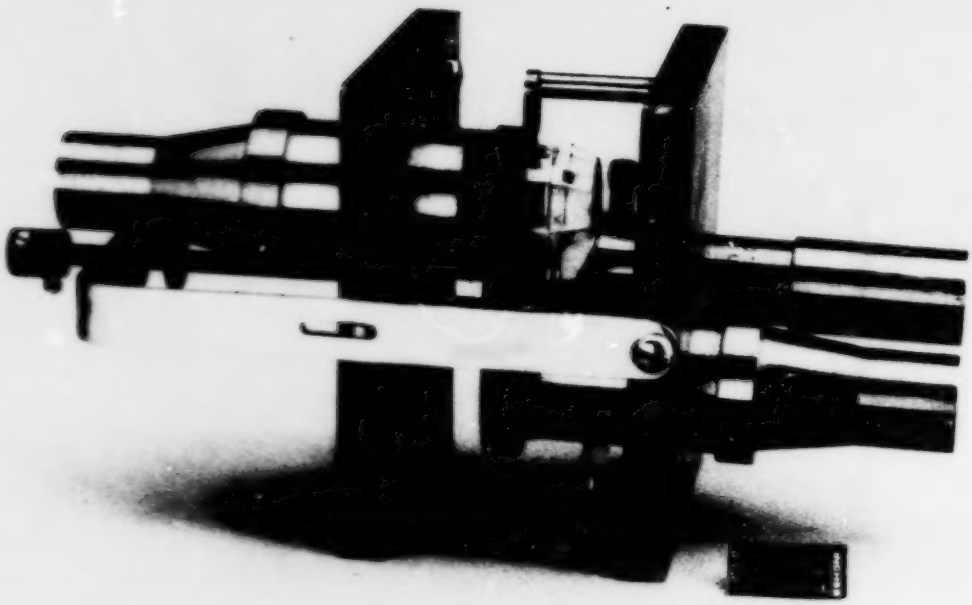

Figure 3b. Sealing device with DCA valve holding block.

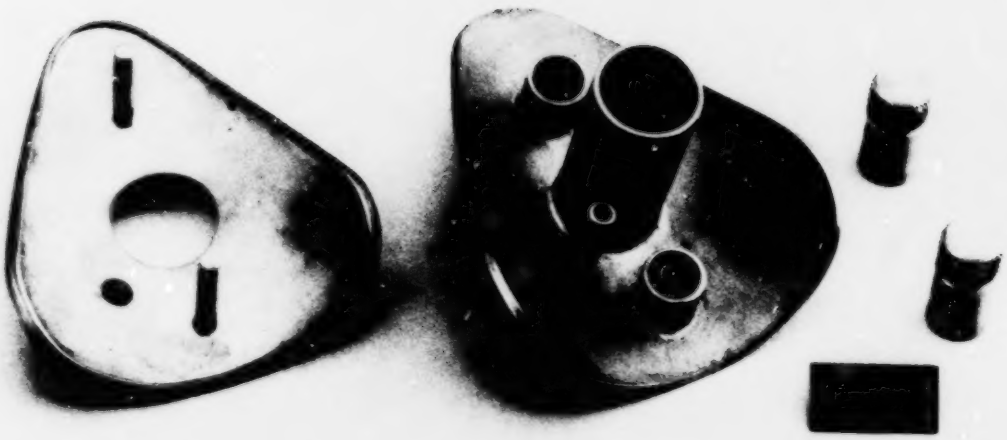

Figure 4a. Sealing device for W oxygen mask face piece with air flow and mask cavity pressure ports.

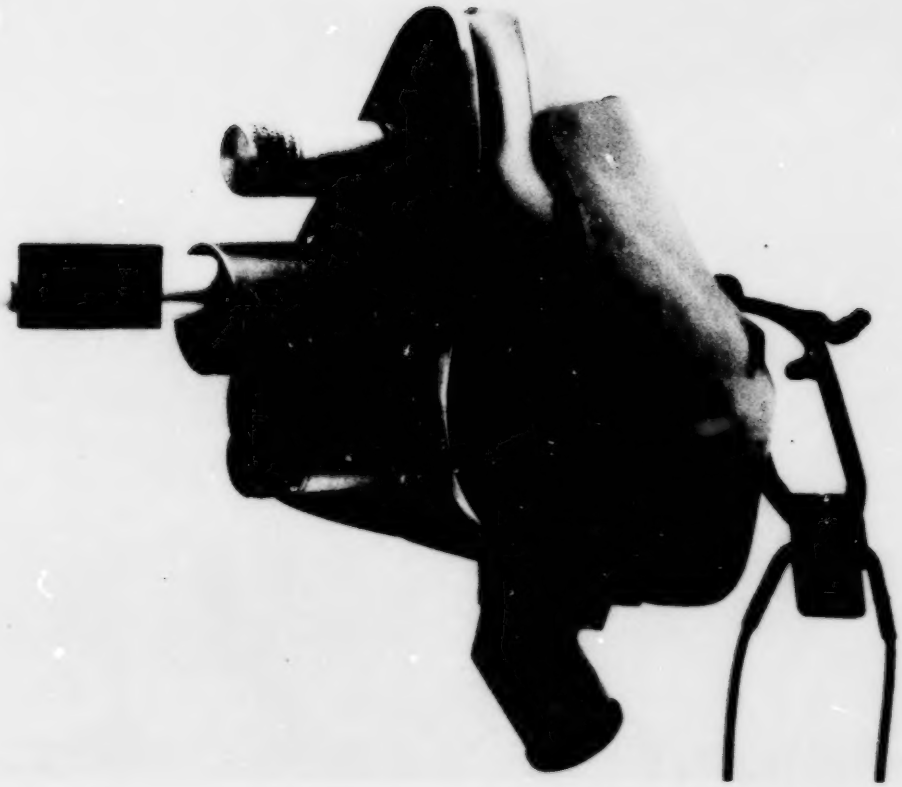

Figure 4b. Sealed face piece of W oxygen mask.

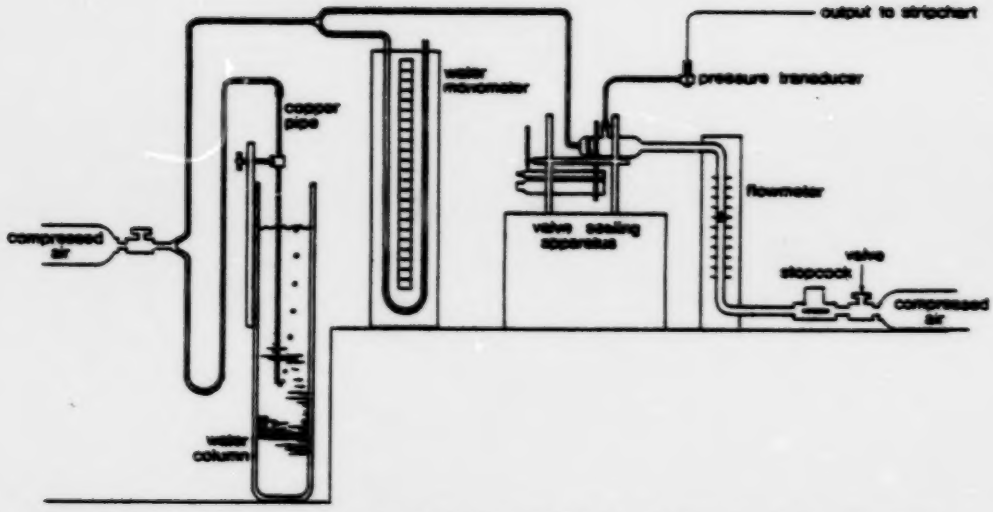

Figure 5. Layout for testing expiratory valve and compensation pressure.

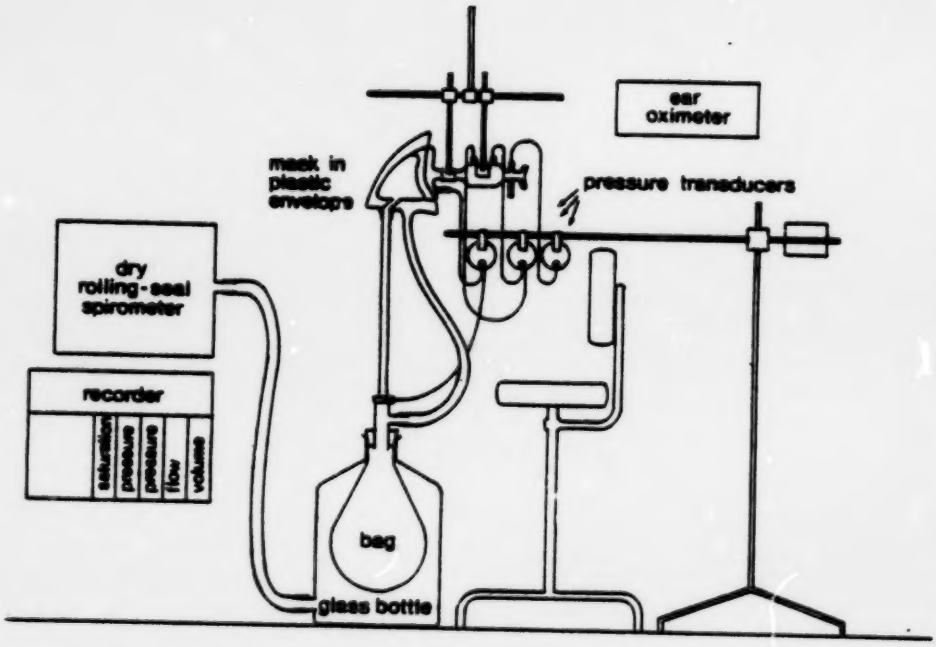

Figure 6. Layout for dynamic tests.

Figure 7. Sealed face piece of W oxygen mask in nylon envelope for dynamic tests.

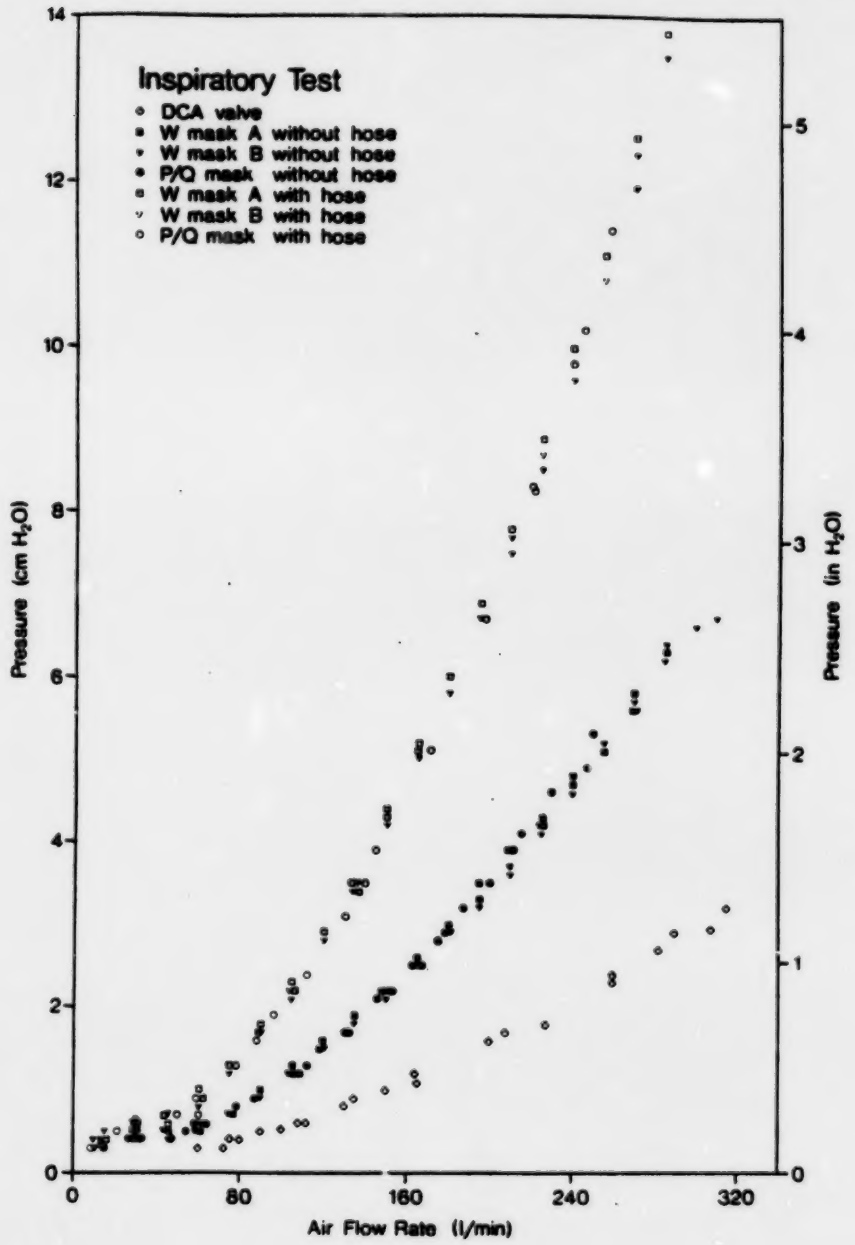

Figure 8. Mask cavity pressures measured at various inspiratory flows.

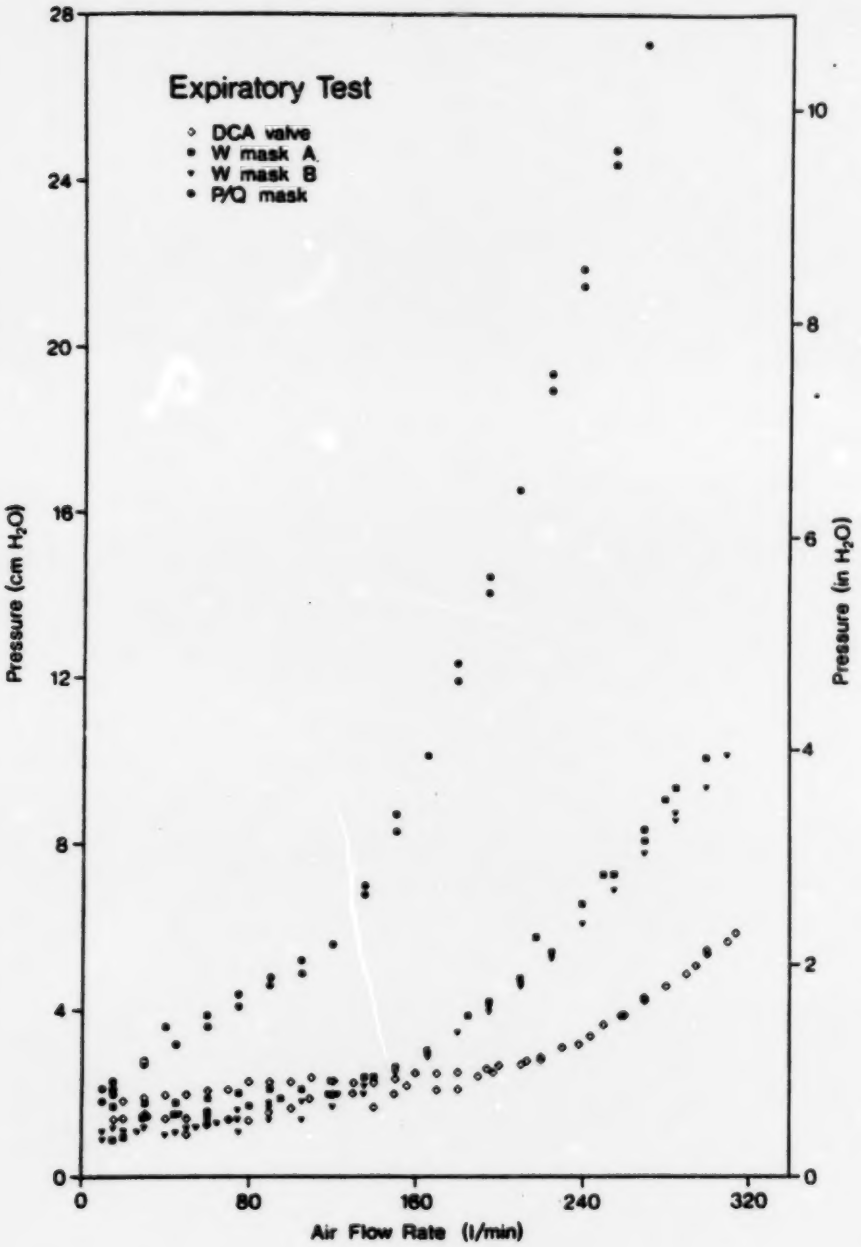

Figure 9. Mask cavity pressures measured at various expiratory flows.

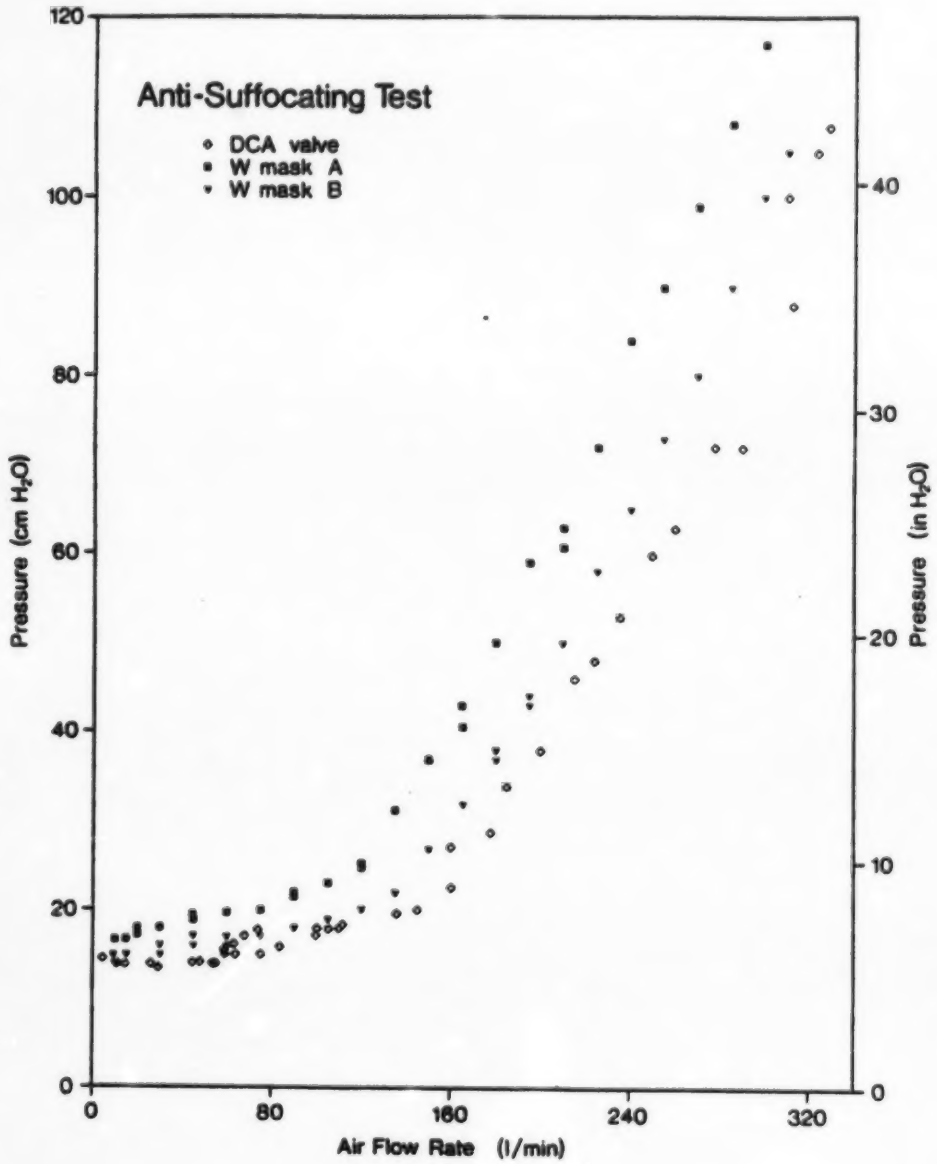

Figure 10. Mask cavity pressures measured at various inspiratory flows through anti-suffocation valve.

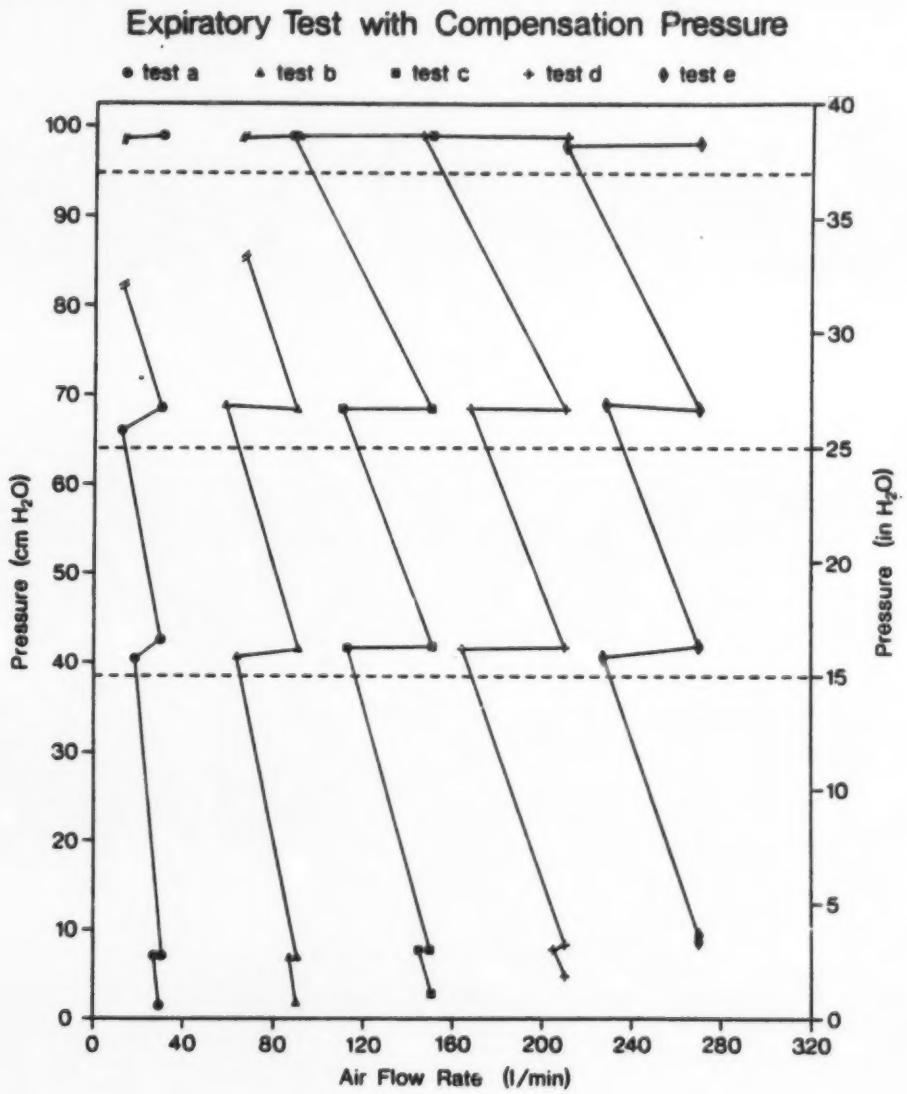

Figure 11. Change in mask cavity pressure and air flow rate with compensation pressure (——) on expiratory valve of W mask.

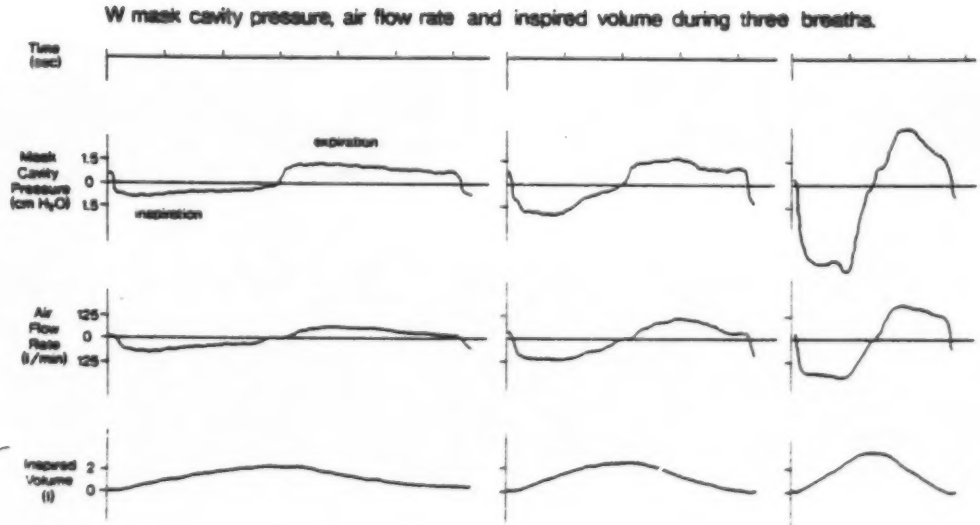

Figure 12. Events during dynamic test.

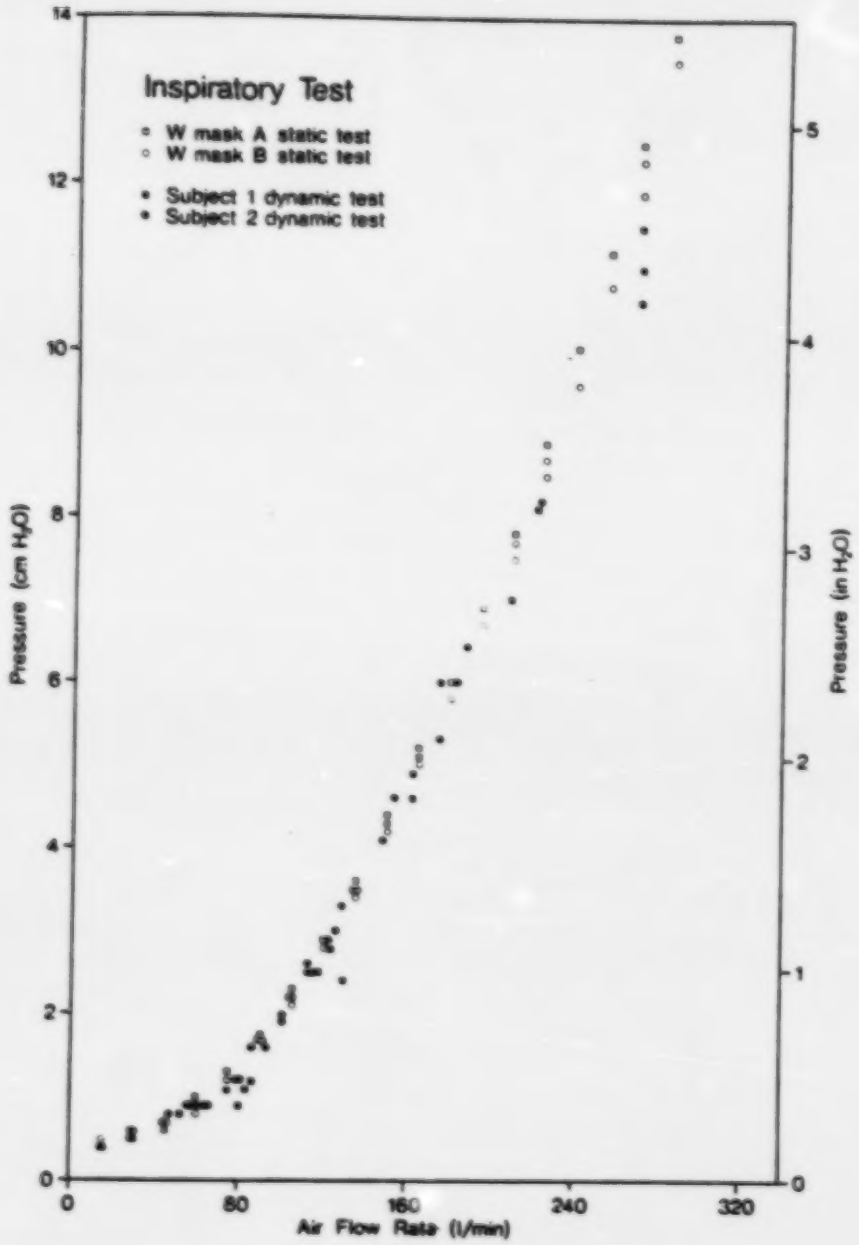

Figure 13. Mask cavity pressures measured at various inspiratory flow rates during static and dynamic tests.

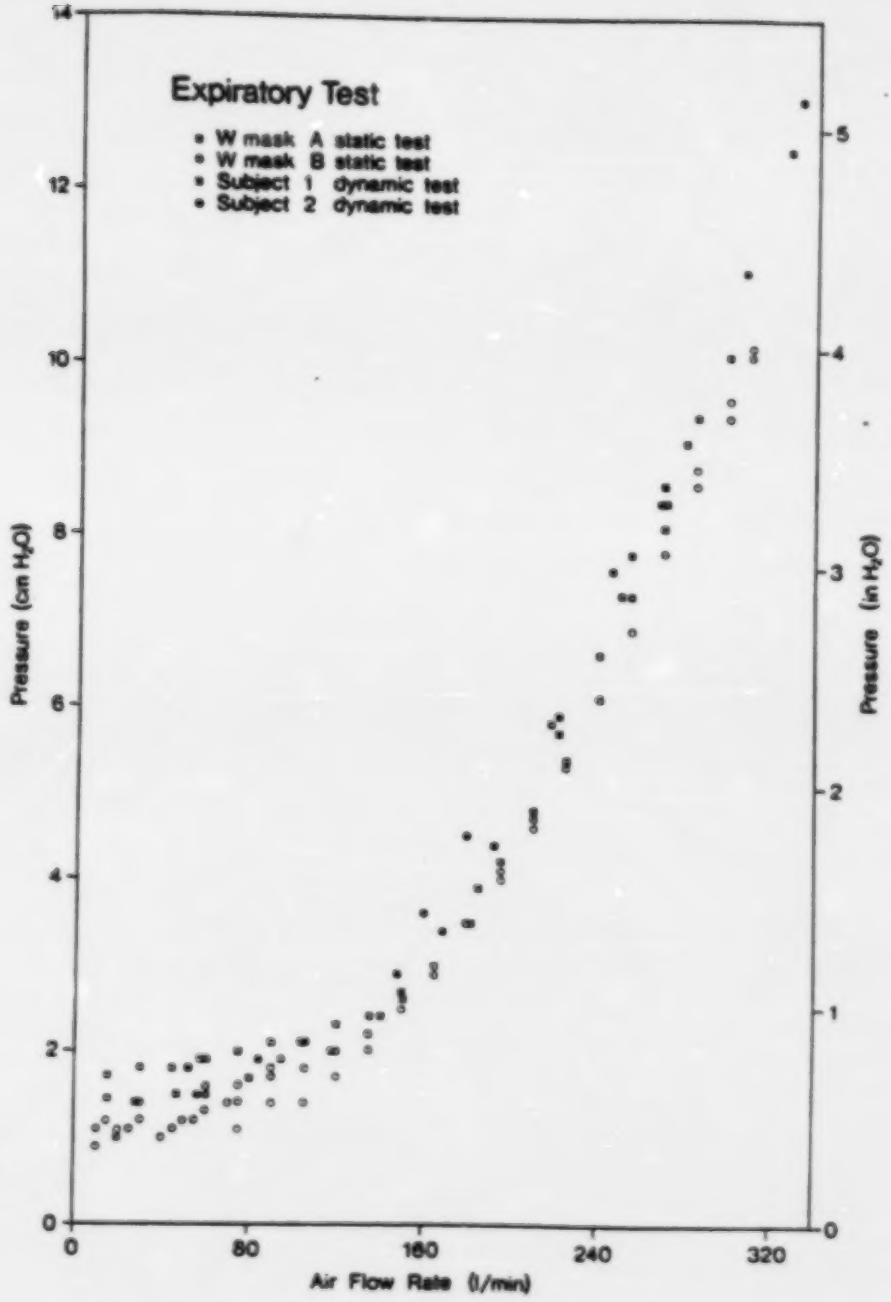

Figure 14. Mask cavity pressures measured at various expiratory flow rates during static and dynamic tests.

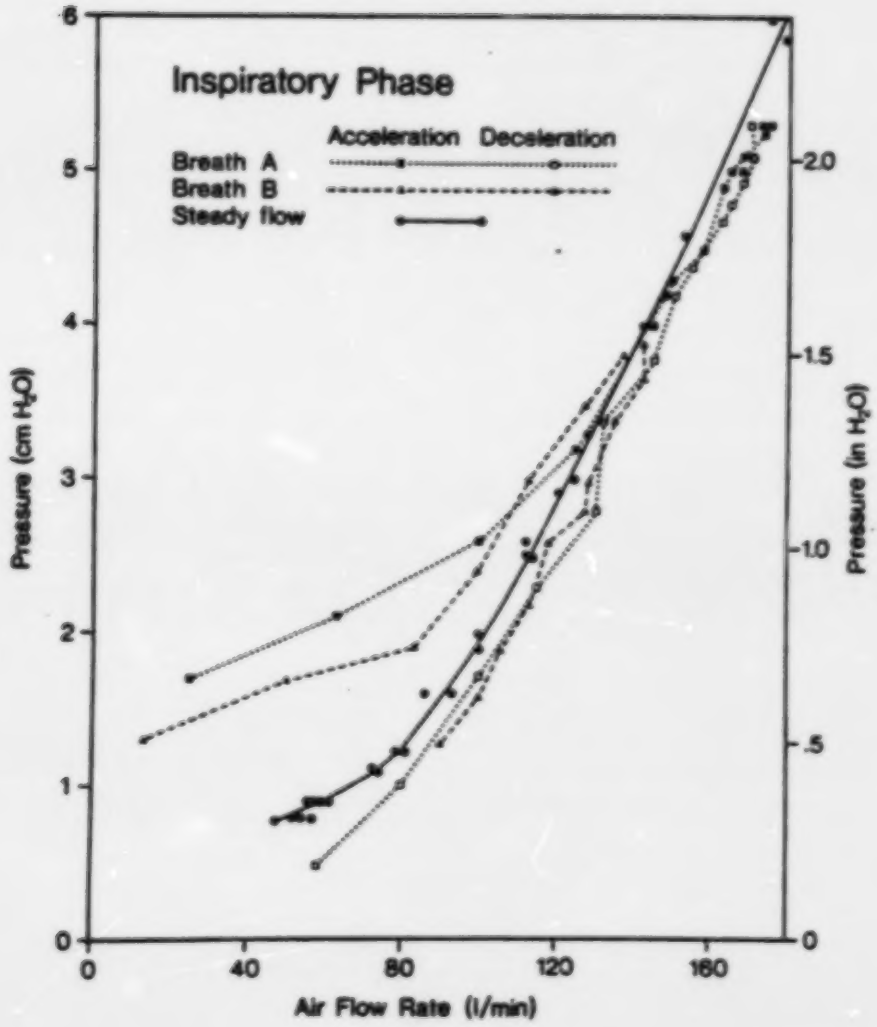

Figure 15. Mask cavity pressures measured during various accelerating, decelerating and constant inspiratory flow.

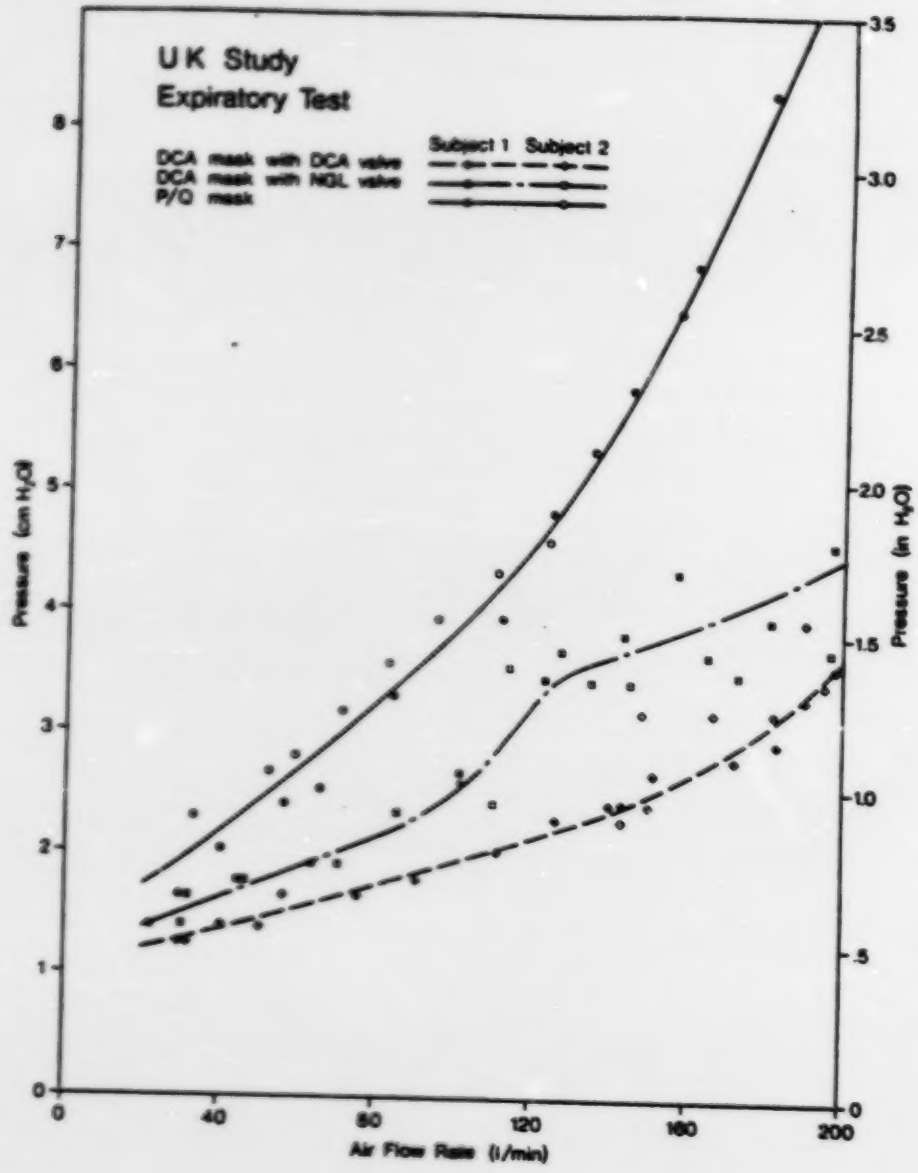

Figure 16. Mask cavity pressures measured at various expiratory flow rates.

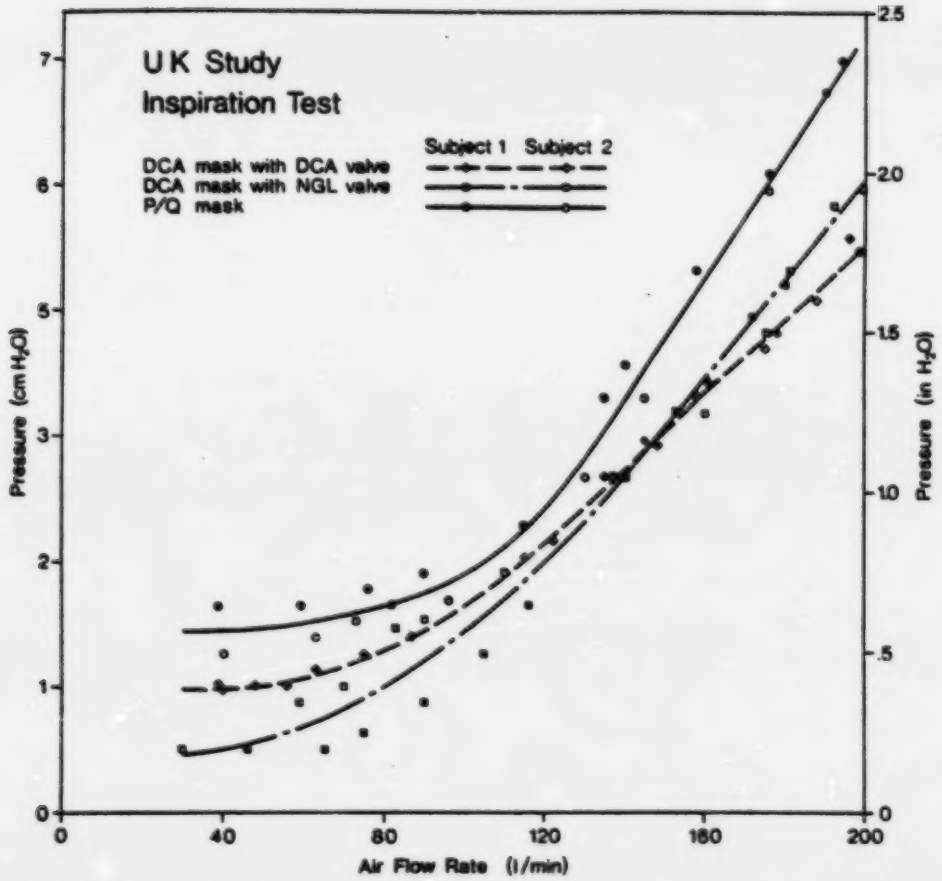

Figure 17. Mask cavity pressures measured at various inspiratory flow rates.

Table 1. Flow-resistance* during inspiration

Flow range (l/min)	Test condition		
	DCA valve	mask	mask & hose
10 - 80	0.04	0.34	0.83
160 - 280	0.80	1.85	4.13

*resistance units - cm H_2O/l/sec

Table 2. Flow-resistance* during expiration

Flow range (l/min)	Test condition		
	DCA valve	W Mask	P/Q mask
10 - 80	0.23	0.23	2.10
160 - 240	0.75	2.48	9.75

*resistance units - cm H_2O/l/sec

Table 3. Flow-resistance* during inspiration through anti-suffocation valve

Flow range (l/min)	Test Item DCA valve	W mask A	W mask B
10 - 120	2.8	3.0	4.8
180 - 280	24.3	28.8	32.1

*resistance units - cm H_2O/l/sec

Table 4. ASCC recommendations (1)

Peak inspiratory and expiratory flow (l/min)	Maximum change of mask cavity pressure during respiratory cycle cm H_2O	in H_2O
30	4.06	1.6
90	6.1	2.4
150	10.2	4.0
200	15.2	6.0

Table 5. Comparison of W mask results.

Test*	Normalair-Garrett Ltd Results* Pressure-in H_2O or Flow l/min						D.C.I.E.M. Results				Lazowski and Forlier
	Mask						Mask				Mask
	1	2	3	4	5	6	A	B			A
Inspiratory Test-Static											
at: Flow (l/min)											
100	0.9	0.9	0.82	0.85	0.85	0.85	0.8	0.8			(dynamic)
150	1.85	1.85	1.77	1.80	1.70	1.70	1.7	1.6	-	-	0.6
200	3.1	2.8	2.70	2.90	2.95	2.60	2.8	2.7	-	-	1.3
											1.8
Anti-Suffocation Valve											
Flow at: -7 in H_2O	68	78	63	64	77	86	35	90			
Pressure at 10 l/min	5.2	5.55	5.50	5.95	6.0	5.70	6.6	5.5	-	-	-
Expiratory Test-Static											
at: Flow (l/min)											
100	0.85	2.0	0.90	1.0	0.70	0.80	0.8	0.6			
150	1.25	2.45	1.10	2.05	1.20	1.20	1.0	1.0	-	-	-
200	2.1	2.90	1.80	1.90	2.10	1.90	1.7	1.6			
Expiratory Test-Dynamic											
at: Flow (l/min)											
100	0.82	1.0	1.10	0.97	0.85	0.77		0.8+	0.8++		0.75
150	2.15	1.70	1.20	1.22	1.04	0.95		1.1	1.2	-	1.0
200	2.50	1.90	1.63	1.70	1.78	1.75		1.9	-		1.4
Compensation Characteristics											
Compensation Pressure (in H_2O) / Flow (l/min)											
10	0.1	-1.0	0.25	-0.2	-0.15	-0.1					
	0.15	-0.1	0.35	-	-0.05	-0.4					
37.4 100	-1.0	1.1	1.2	-1.0	0.75	1.37					
	-	1.3	1.65	1.0	1.2	1.4					
200	-0.4	-0.1	0.65	-0.2	-0.2	0.35					
	-1.0	0.75	0.95	0.15	1.2	0.55					
30											
37.4 150							1.6				
210							1.6				
							1.6				

* Reproduced from Reference 6.
\+ Subject 1
++ Subject 2

POOR

QUALITY

ORIGINAL